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L. Broom and G.D.M. Cameron

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SUMMARY

Improved bathymetric data along with legacy seabed samples and seismic profile data have allowed for enhanced understanding of the surficial geology and seafloor morphology of Flemish Cap. Three surficial geology units are mapped: bedrock, till, and patchy sand and gravel cover. The bedrock units include a Neoproterozoic granite and granodiorite unit in the center of Flemish Cap, which is overlain by Cretaceous to Cenozoic sedimentary rocks. These units have then been overlain by till. A patchy sand and gravel deposit covers most of Flemish Cap, and was deposited mostly through ice-rafted debris and redistributed by the Labrador and the North Atlantic Currents. The improved bathymetric data has revealed megascale glacial lineations (MSGLs) incised mostly in soft bedrock or till and eroded bedrock lineations located on eastern and southern Flemish Cap. A glacial moraine has been identified for the first time on the north side of Flemish Cap. These glacial features are evidence of a late Quaternary glacial ice cap on Flemish Cap.

INTRODUCTION

Flemish Cap is an isolated continental basement high (Pe-Piper, 2018), found in the North Atlantic 600 km east of Newfoundland, with water depths as little as 123 mbsl. It is separated from the Grand Banks by the deep waters of Flemish Pass (Figure 1). Sackville Spur and Orphan Basin lie to the northwest of Flemish Cap, and Beothuk Knoll to the southwest. Flemish Cap formed during the opening of the Atlantic throughout the Mesozoic. Flemish Cap acted as a microplate as the Iberian and North American plates were rifting, (Hopper et al., 2007). Flemish Cap separated from Galicia Bank as a volcanic ridge formed between North America and Iberia around 118 ma (Srivastava & Verhoef, 1992).

Geological investigations on Flemish Cap have focused on bedrock composition (King, 1985; Pelletier, 1971; Grant 1973) and surficial geology studies around its flanks (Weitzman et al., 2014 and Miles, 2018). Flemish Cap consists of a central core of Neoproterozoic berock consisting primarily of granite and granodiorite, which is surrounded and onlapped by Cretaceous to Tertiary sedimentary rocks. This bedrock sequence has been overlain by glaciogenic and marine sediments.

It has been suggested that there was an ice cap on Flemish Cap during the penultimate glaciation (MIS 6) (Stacey, 2011; Piper, 2018). This has been inferred by the presence of deposits interpreted as buried till from SE Flemish Cap in seismic data (Stacey, 2011). Shaw suggested that during the Last Glacial Maximum (LGM), Flemish Cap was not likely glaciated and sea level was up to 110-120 m lower than present day. This would have likely put some of Flemish Cap close to sea-level, causing high-wave energy to rework sediments (Shaw, 2006).

The Labrador Current (LC) and the North Atlantic Current (NAC) are the two major water currents affecting sediment distribution on Flemish Cap. The LC carries cold, less saline waters on a southerly flow along the Labrador Slope. It splits around Flemish Cap, traveling over Flemish Pass and clockwise around the cap (Stein, 2007; Colbourne and Foote, 2000). It also brings icebergs which drop sediment debris across the cap. The NAC, brings warmer, more saline waters from the Gulf of Mexico along the northeastern side of the cap. Both currents winnow surficial sediment across Flemish Cap (Colbourne and Foote, 2000).

New Olex bathymetric data has greatly improved the resolution of the seafloor morphology on Flemish Cap, which allow for updated mapping and interpretation of the surficial features and geology of the cap. There is also high resolutions multibeam bathymetry collected from the 2009-2010 Nereida Program cruises, although these only cover the slopes of the cap and have virtually no overlap with the Olex bathymetric data on Flemish Cap. Updated surficial geology mapping will improve understanding of seabed conditions and the potential environmental impact of hydrocarbon exploration and development in the region.

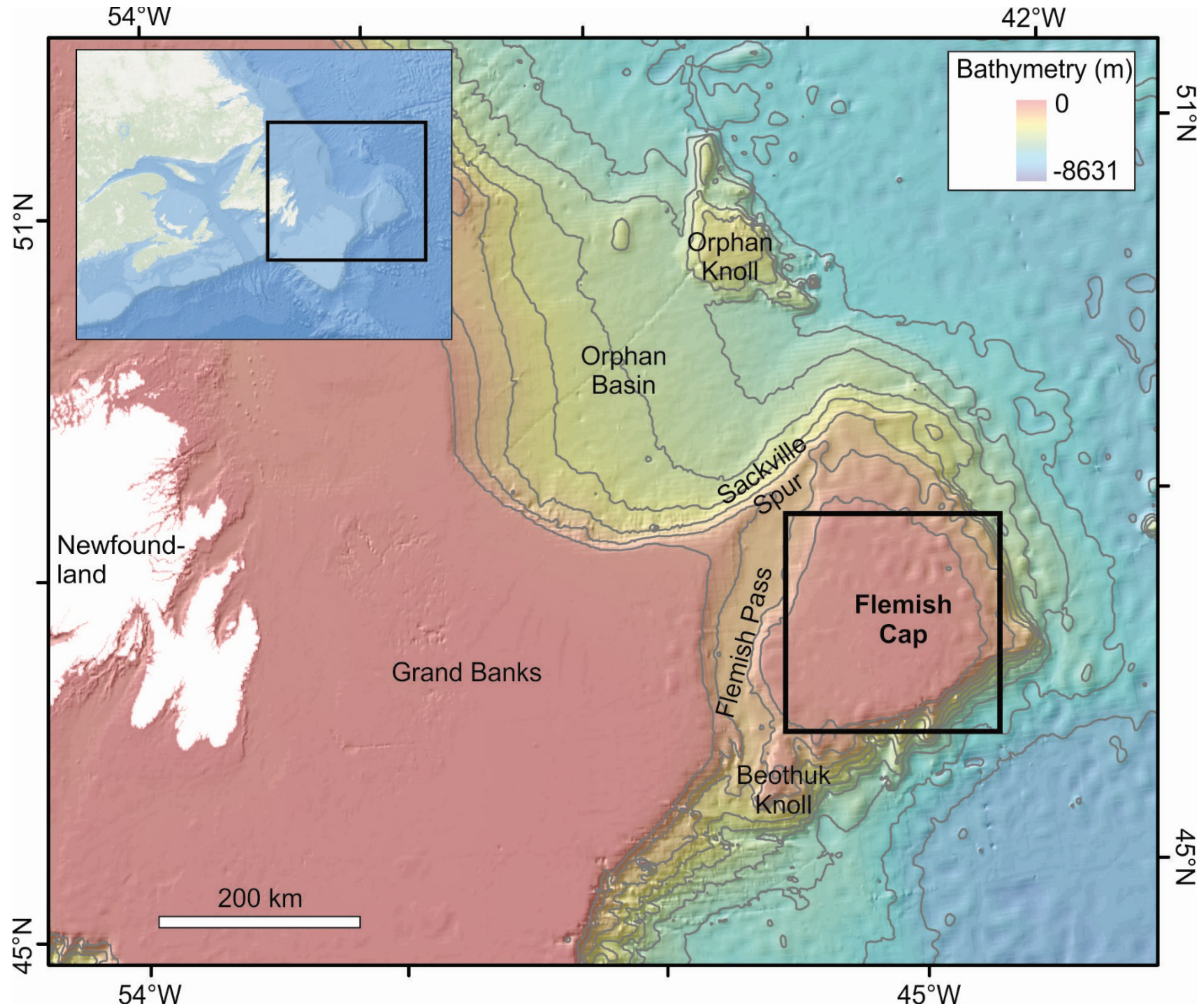

Figure 1 *Flemish Cap is an isolated fragment of continental crust located in the North Atlantic 600 km east of Newfoundland. It is separated from the Grand Banks by the deep waters of Flemish Pass. Underlying GEBCO bathymetric data and shaded relief image (OC, IHO, & BODC 2003).*

DATA AND METHODS

Bathymetric data

Olex is a bathymetric database used for mapping and navigation, where users are encouraged to share seafloor echosounder data. These bathymetric data were collected using standard commercial single-beam echosounders and GPSs, with a resolution of up to 5 m (oceanDTM, n.d.).

Olex bathymetric data were used to create a digital terrain model to visualize the seafloor morphology on Flemish Cap. The data were visualized in ArcGIS version 10.6.1 by creating shaded relief and gradients of the bathymetry over Flemish Cap and its surrounding area (Figure 2). Shaded relief images were created with Azimuths of 225°, 315°, 90° and 45°, and an altitude of 45°.

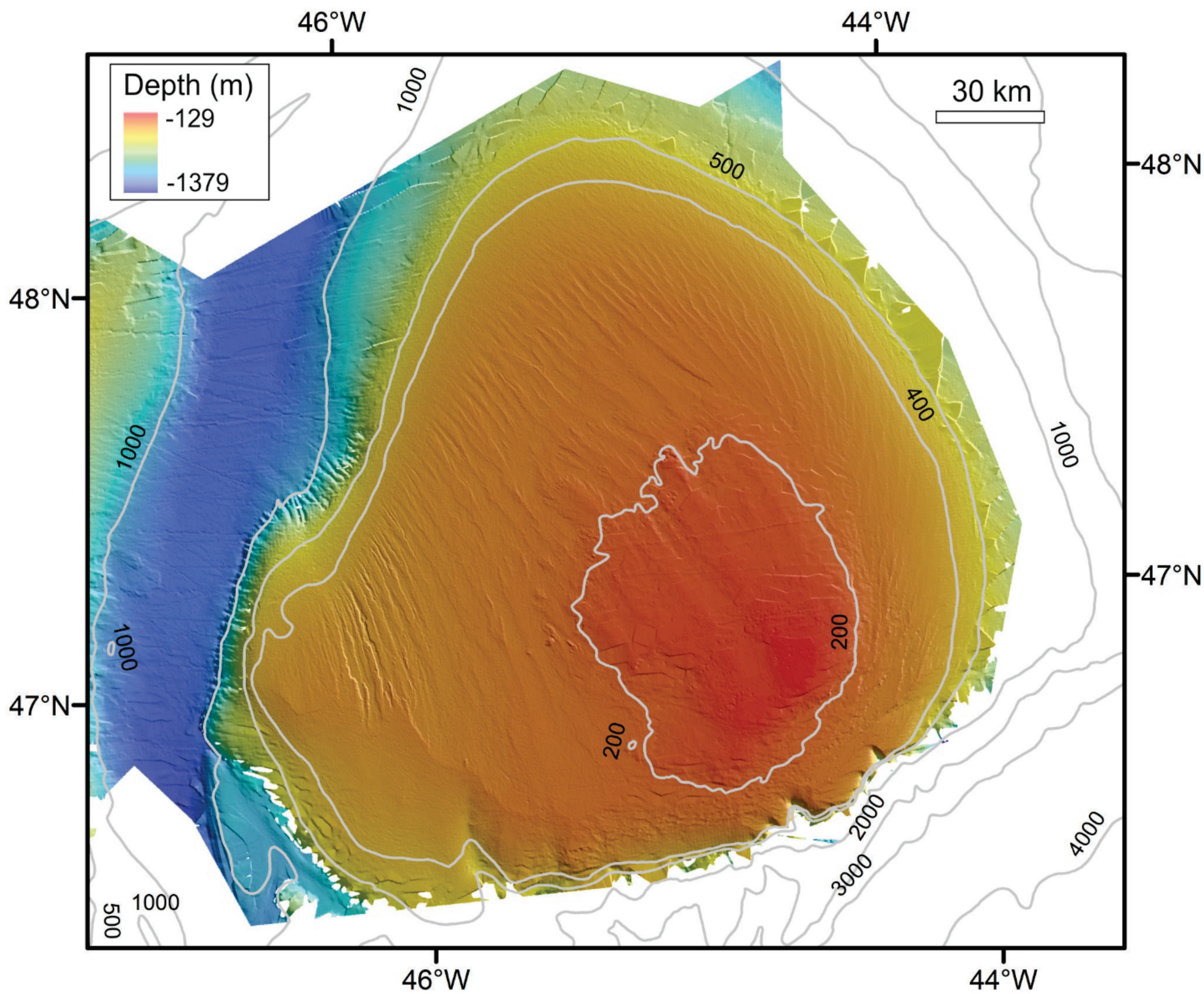

Figure 2 *A digital terrain model from Olex bathymetric data across Flemish Cap and Flemish Pass (oceanDTM, n.d.). This colourized digital shaded-relief model, with bathymetric contours, highlights the broad, flat and highly erosional morphology of Flemish Cap.*

Seismic reflection data

Legacy seismic reflection profile data, of varying quality, collected from 1969 to 2001, by the Geological Survey of Canada (GSC) were used to map the surficial geology of Flemish Cap. The surficial geology units were primarily mapped using 2400 km of Huntec and 3.5 kHz seismic reflection profiles collected from 1975-2001 (Figure 3a). Approximately 2700 km of airgun seismic reflection data, collected from 1969-2001, were used where there was little to no acoustic penetration by high resolution seismic data (Figure 3b).

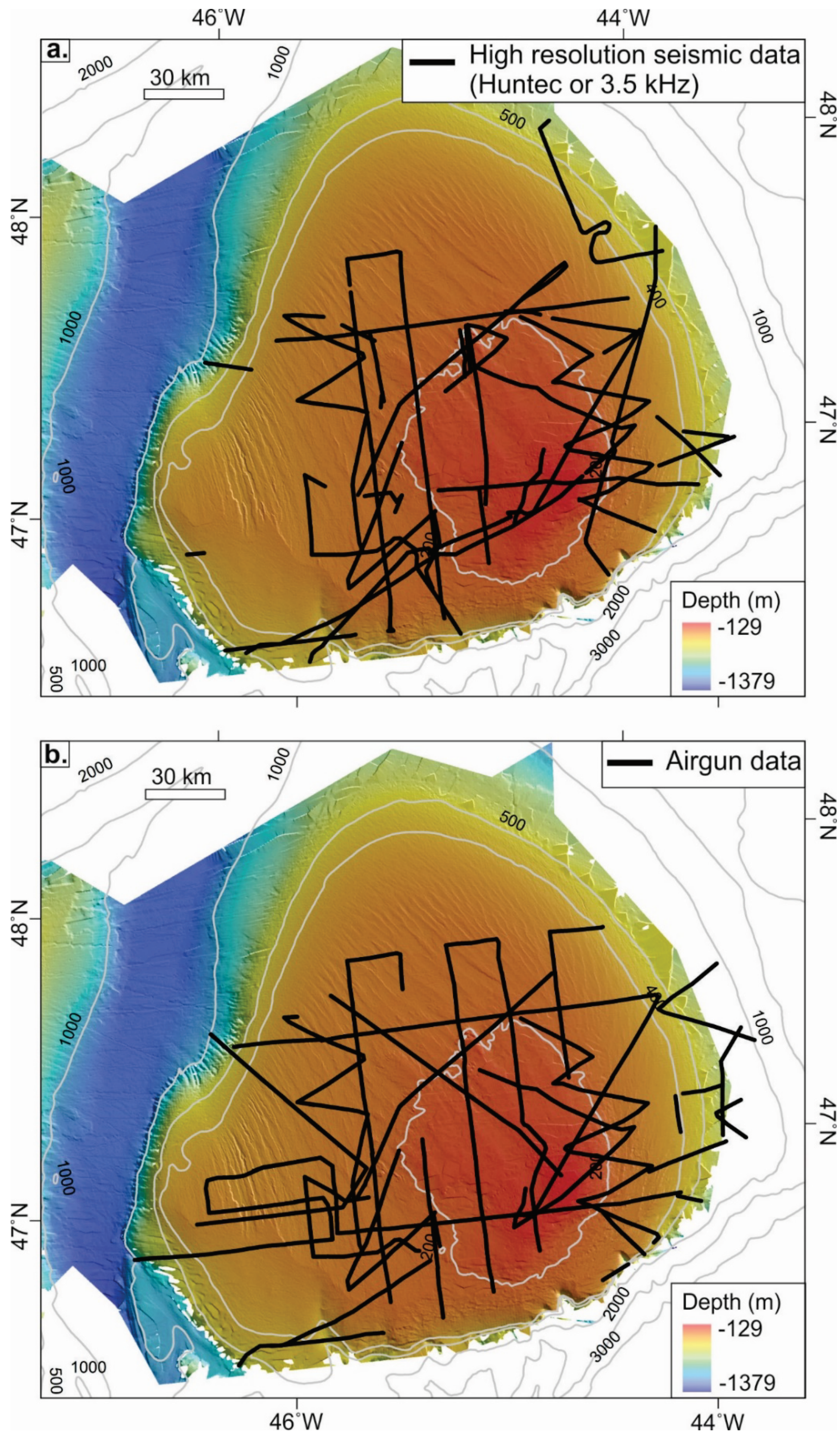

Figure 3 *a) High resolution Huntec and 3.5 kHz seismic reflection data coverage and b) Airgun seismic reflection data coverage used for interpreting the surficial geology of Flemish Cap. Olex colourized digital shaded-relief model underlies seismic lines (oceanDTM, n.d.).*

Surficial sediment samples

Forty eight surficial sediment samples, including box cores, grab samples and a vibrocore, collected by the GSC from the 1970s through the 2000s, have been used to obtain grain size data. These grain size data supported the selection of surficial map boundaries on Flemish Cap (Figure 4).

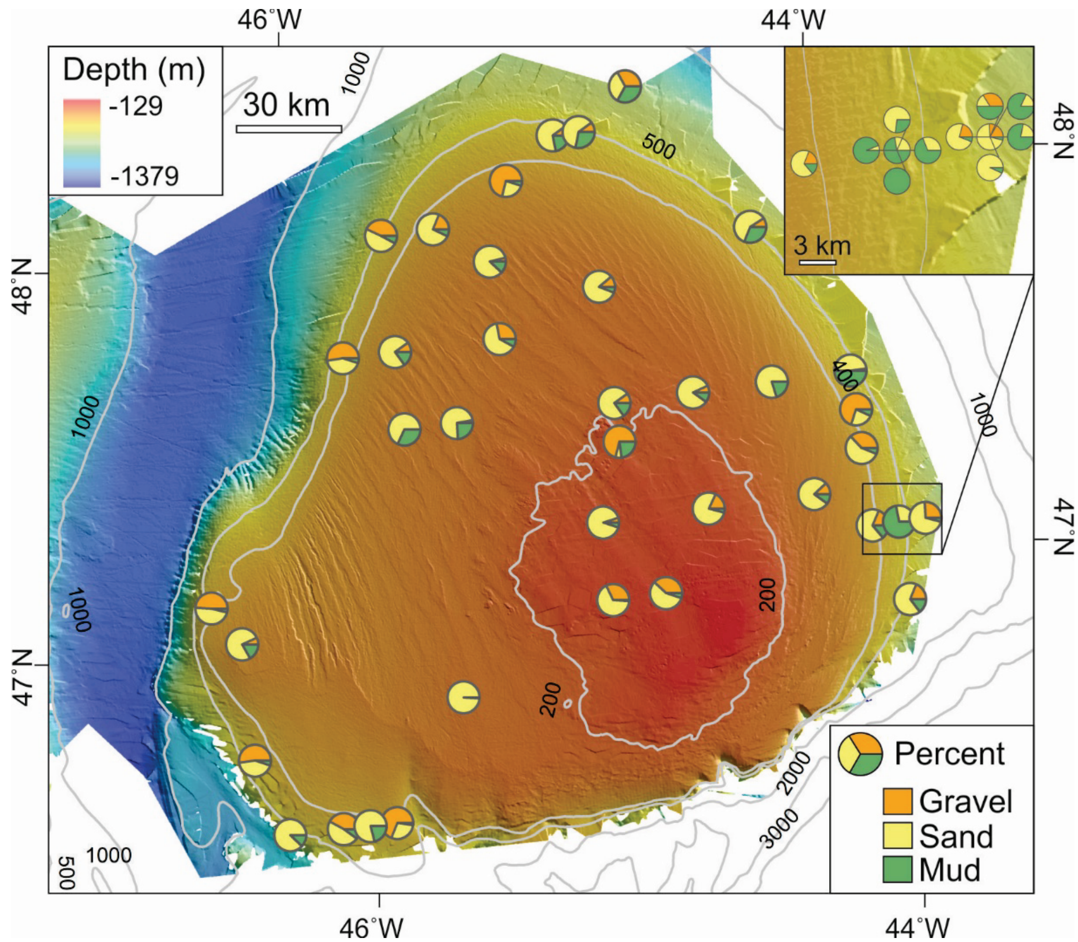

Figure 4 *Grain size data from surface sediment samples collected on Flemish Cap showing percentage of gravel, sand and mud in each sample. Olex colourized digital shaded-relief model underlies samples (oceanDTM, n.d.).*

SURFICIAL GEOLOGY

Three surficial geology units have been identified and mapped: bedrock, till, and patchy sand and gravel cover (Figure 5).

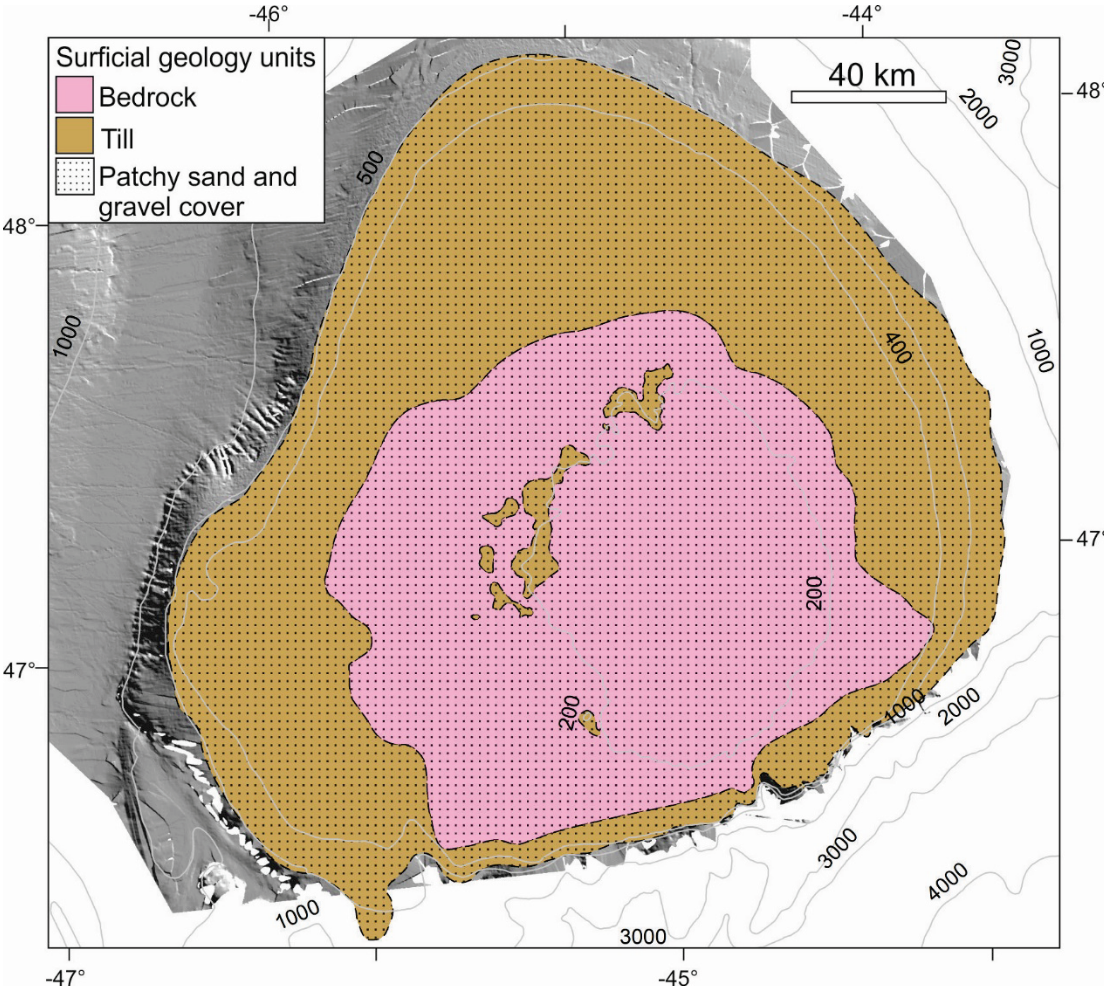

Figure 5 *Surficial geology of Flemish Cap including bedrock, till and patchy sand and gravel lag which covers cover over all units. Olex digital shaded-relief model underlies the map. Interpreted boundary between units denoted by dashed line (oceanDTM, n.d.).*

Bedrock

The surficial geology map includes one bedrock unit composed of two distinct bedrock types. The bedrock geology can be subdivided based on seismic profile data (Figure 6; Figure 7; Figure 8). It includes a Neoproterozoic bedrock core surrounded by onlapping Cretaceous to Cenozoic (K-C) sedimentary rocks as recognized by, King and Fader, (1985) and Grant, (1973). Reinterpretation of the legacy airgun data and the inclusion of the new bathymetric data lead to the production of an updated bedrock map from King and Fader (1985). This map demonstrates the bedrock beneath the sand, gravel and till cover.

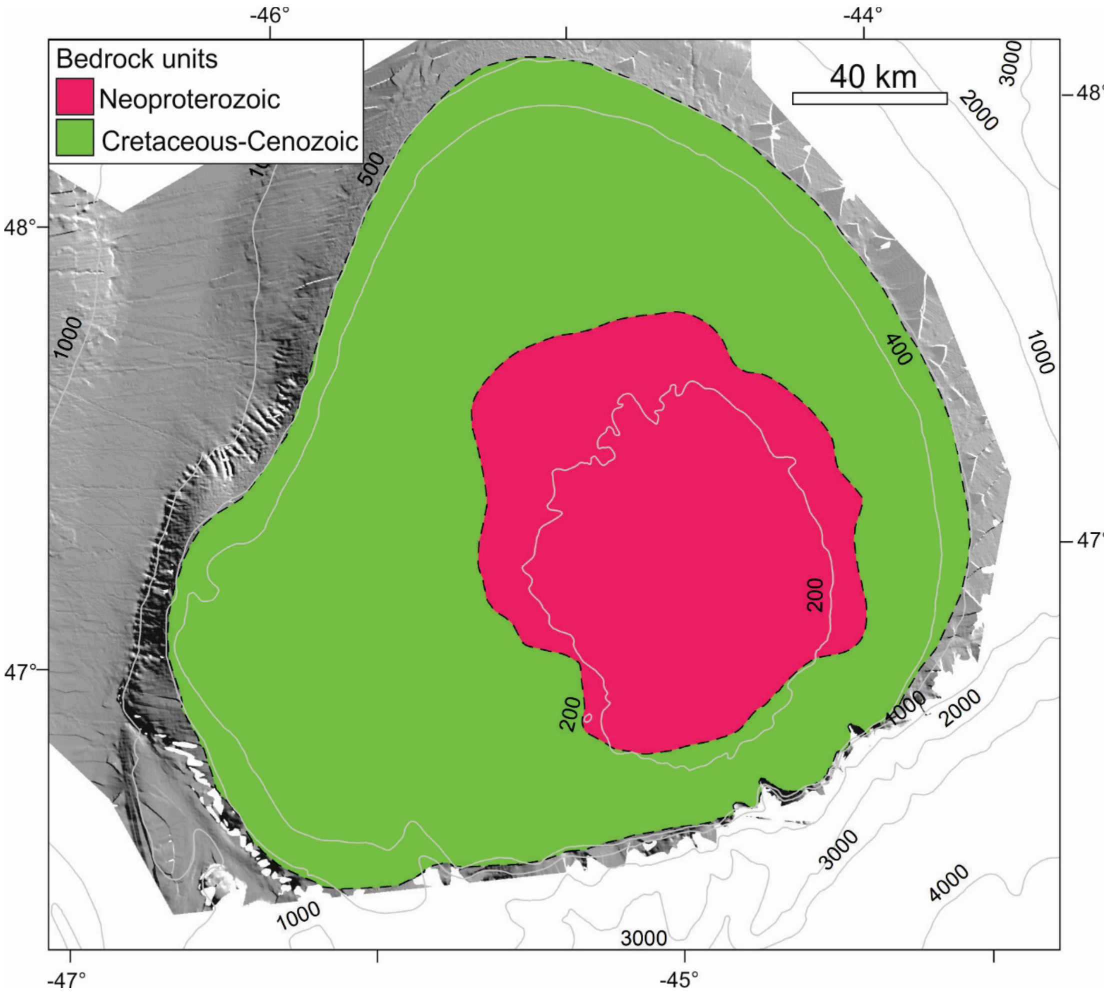

Figure 6 *Bedrock units of Flemish Cap including Neoproterozoic granodiorite and granite surrounded by onlapping Cretaceous to Cenozoic sedimentary rocks. These rock units are overlain by glacial till and sand and gravel deposits, (see Fig. 5). Olex digital shaded-relief model underlies map* (oceanDTM, n.d.). *Interpreted boundary between units denoted by dashed line.*

Neoproterozoic bedrock

The Neoproterozoic bedrock has a highly reflective seismic character at the seabed, with no continuous, coherent internal reflections. The bedrock morphology in seismic profiles at the seabed can range from smooth to rough (Figure 7). Drill cores, collected by King and Fader (1985), confirm that the bedrock consists of granodiorite and granite, along with metasedimentary and metavolcanic rocks of the Avalon terrane found in Newfoundland. Post-glacial sand and gravel sediment cover infills this morphology and smooths the seafloor, (Figure 7).

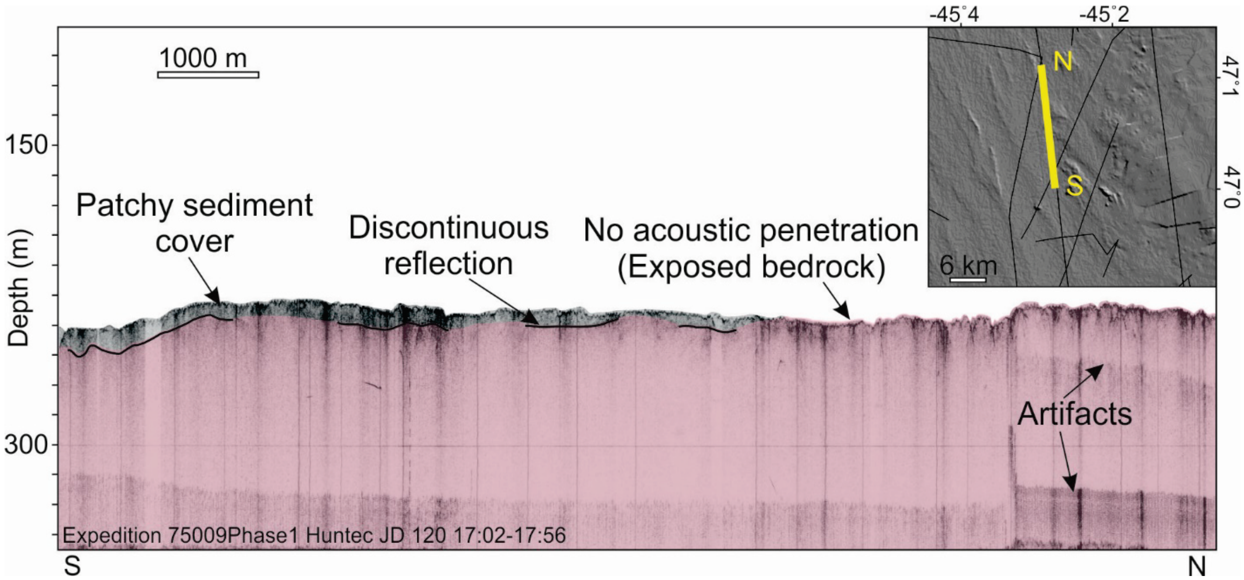

Figure 7 *Huntec seismic reflection profile showing Neoproterozoic bedrock with patchy overlying sand and gravel, up to 5 m thick. Olex shaded-relief inset map shows location of seismic profile* (oceanDTM, n.d.).

Cretaceous to Cenozoic sediments

Seismic profile data show dipping (2-3 degrees) stratified parallel reflectors unconformably onlapping the Neoproterozoic granitic bedrock core of Flemish Cap. It was concluded from Box cored material collected by Grant, (1973) that these sediments are early Cretaceous to Cenozoic (K-C) in age and consist of carbonate and clastic rocks including siltstone, mudstone, and sandstone. King et al., (1985) suggests that the lower part of this sequence may have been deposited before rifting occurred along the eastern margin of Flemish Cap.

In western and southwestern Flemish Cap the onlapping K-C sediments are folded and faulted, as illustrated in Figure 8a and 8b. King, et al., (1985) speculated that the minor folding and faulting occurred during rifting movements associated with the development of Flemish Pass. Seismic control across this area is insufficient to map the complex structural relationships in detail. These reflectors are often truncated at or near the seafloor defining an angular unconformity (Figure 8a). This unit is found over much of Flemish Cap, and the outer limit of the K-C sedimentary rocks is roughly defined by the edge of the cap (Figure 6). There are very few airgun profiles over the edge of Flemish Cap (Figure 3b), and where they exist, there is insufficient acoustic penetration to reveal this boundary.

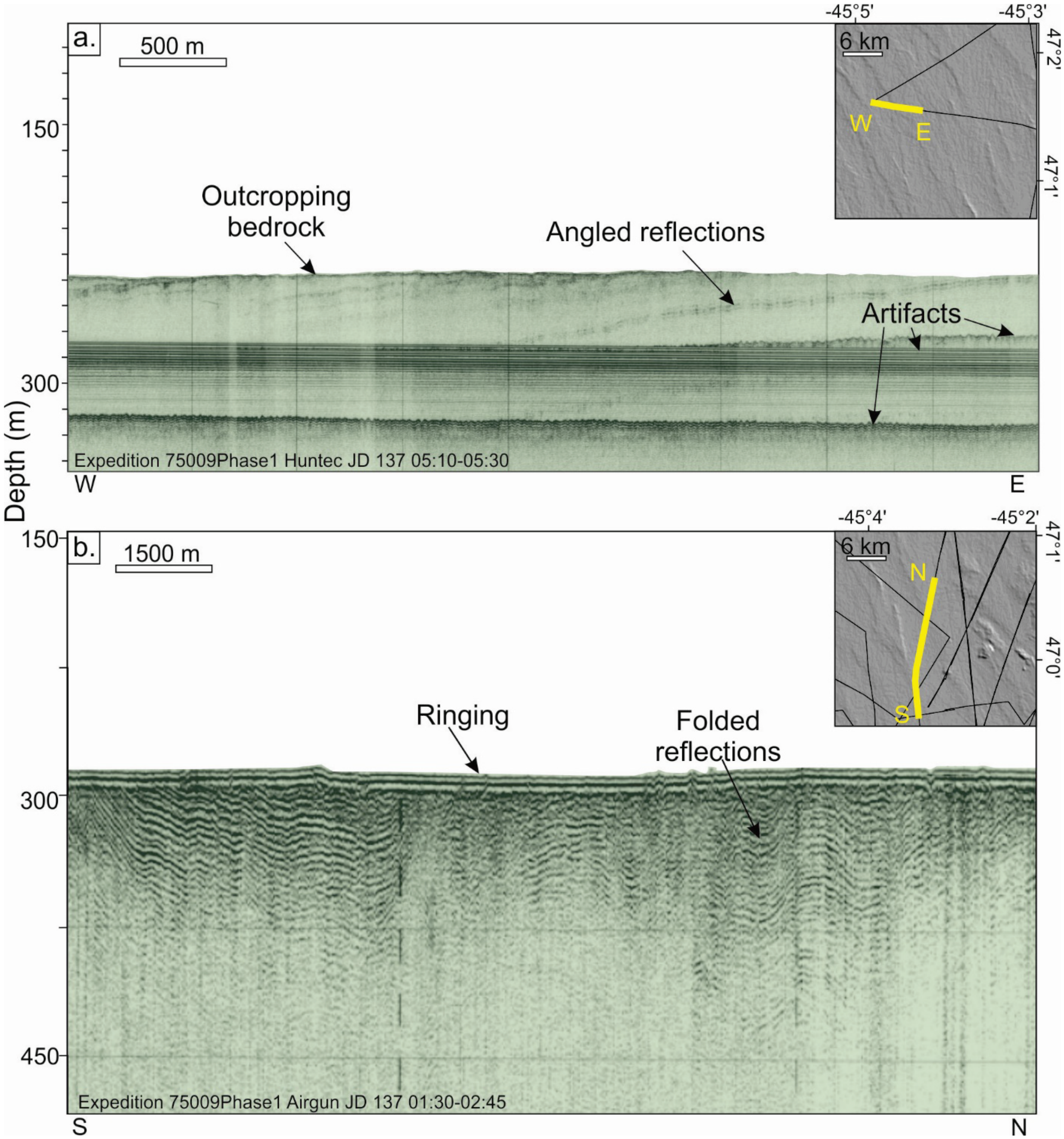

Figure 8 *a) Huntec seismic reflection data showing stratified Cretaceous to Cenozoic sedimentary rocks with truncated dipping beds eroded at the seabed. b) Airgun seismic reflection profile showing folded bedrock reflectors truncated at seafloor. Olex shaded-relief inset map shows location of seismic profiles (oceanDTM, n.d.).*

Till

In water depths greater than approximately 250-300 m, the bedrock units are overlain by an acoustically chaotic to reflection free unit in airgun and Huntec seismic reflection profiles (Figure 9). There is little to no acoustic penetration in this unit observed in Huntec data and the surficial morphology is smooth. In airgun data, this unit appears acoustically chaotic to reflection free. This unit is typically wedge shaped where it pinches out on top of the bedrock units and thickens out to up to >100 m towards the flanks of the cap (Figure 5; Figure 9a; Figure 9b; Figure 9c). It is also observed infilling lows in bedrock morphology (Figure 9a). The infilling nature and wedge shape of this unit along with its acoustically chaotic character in airgun and Huntec seismic profiles could suggest this unit is till.

Reconstructions of the paleogeography of Atlantic Canada over the last 13 ka by Shaw (2006) suggest that the cap was not glaciated during the LGM. However, Stacey (2011) suggests there was an ice cap on Flemish Cap during MIS 6, inferred by the presence of deposits interpreted as buried till along SE Flemish Cap in seismic data (Figure 10). Another possible interpretation for the till unit could be undifferentiated sedimentary bedrock or iceberg turbated sediment forming a sediment wedge. This could account for the chaotic nature of the unit in airgun profiles, and is also supported by the continual influx of icebergs to the area. Core samples would be required to ground-truth the interpretation of the till unit.

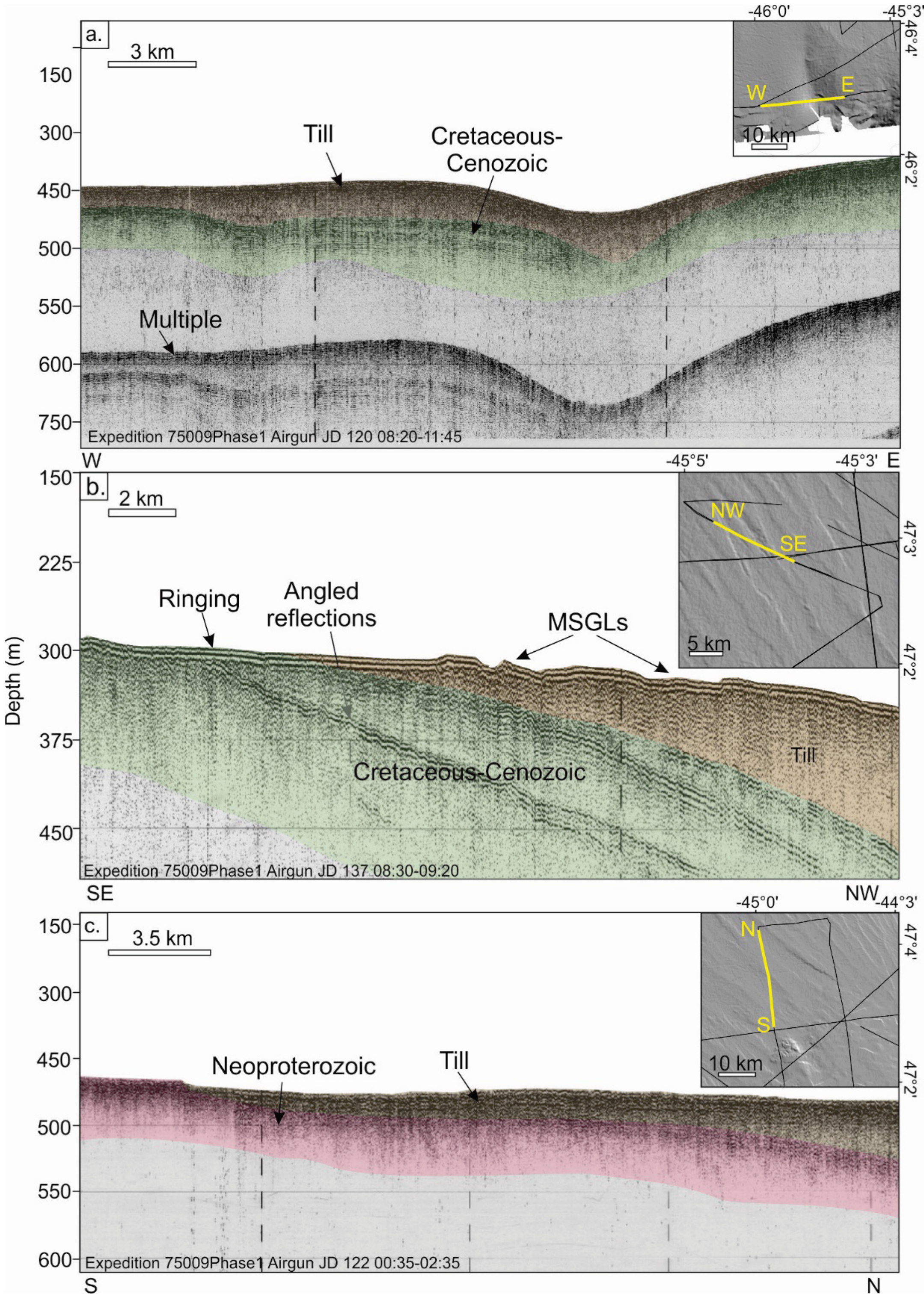

Figure 9 *a) Airgun seismic reflection profile showing acoustically transparent-chaotic unit (till) deposits overlying the K-C sedimentary rocks along the SW region of Flemish Cap. b) Airgun seismic reflection profile showing till above K-C sedimentary rocks in the NE region of Flemish cap. c) Airgun seismic reflection profile showing acoustically transparent-chaotic unit (till) deposits overlying the Neoproterozoic bedrock unit in the NE region of Flemish Cap. Olex shaded-relief inset map shows location of seismic profile (oceanDTM, n.d.).*

Beyond water depths of 500-600 m, a change in acoustic character is observed in Huntec seismic reflection data where there is a transition from an acoustically chaotic unit towards the interior of Flemish Cap to an acoustically well stratified unit towards its perimeter. These are interpreted to be contourite drift deposits surrounding Flemish Cap. This boundary is denoted by the edge of the till unit and marks the edge of the surficial geology map (Figure 5; Figure 10).

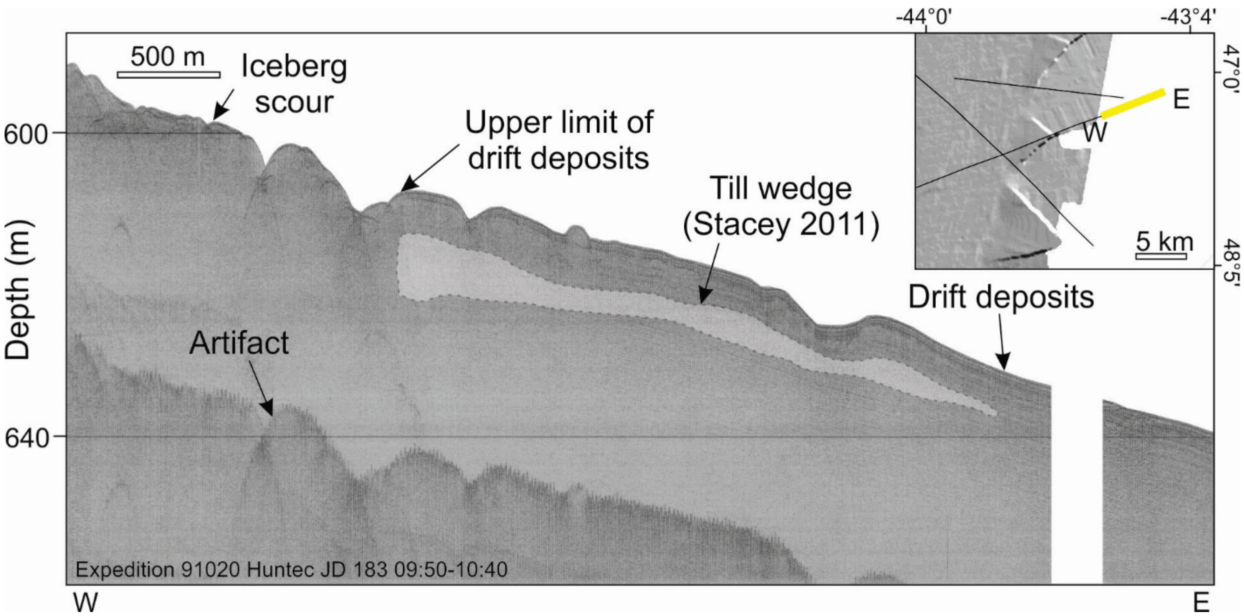

Figure 10 *Sediment drift deposits on the eastern flank of Flemish Cap and a possible till wedge. Olex shaded-relief inset map shows location of seismic profile (oceanDTM, n.d.).*

Sand and gravel

A patchy lag of post-glacial sand and gravel is likely covering much of Flemish Cap above 450 m water depth. The thickness of this sediment cover is challenging to determine based on the limited acoustic penetration of the Huntec seismic profiles. It places it appears <5 m thick (Figure 7b), while in places with no acoustic penetrations it could be tens of meters thick. Miles (2018) and Weitzman et al. (2014) also recognized that the majority of Flemish Cap is covered by a patchy sand and gravel cover. When there is acoustic penetration, moderate parallel undulating reflections are observed in some Huntec seismic reflection profiles which mirror the upper surface (Figure 11a; Figure 11b). The undulatory morphology of these reflections suggests that some of this sand and gravel unit has been sculpted into sediment waves (Figure 11). These large scale bedforms appear to be relatively symmetrical and have amplitudes of 2-5 m and wavelengths of 50-100 m. The sediment waves occur across the cap at depths of 140-340 mbsl. These bedforms are not resolved by the Olex bathymetric data and are only recognized by the Huntec seismic reflection profiles, therefore it is difficult to distinguish their orientation.

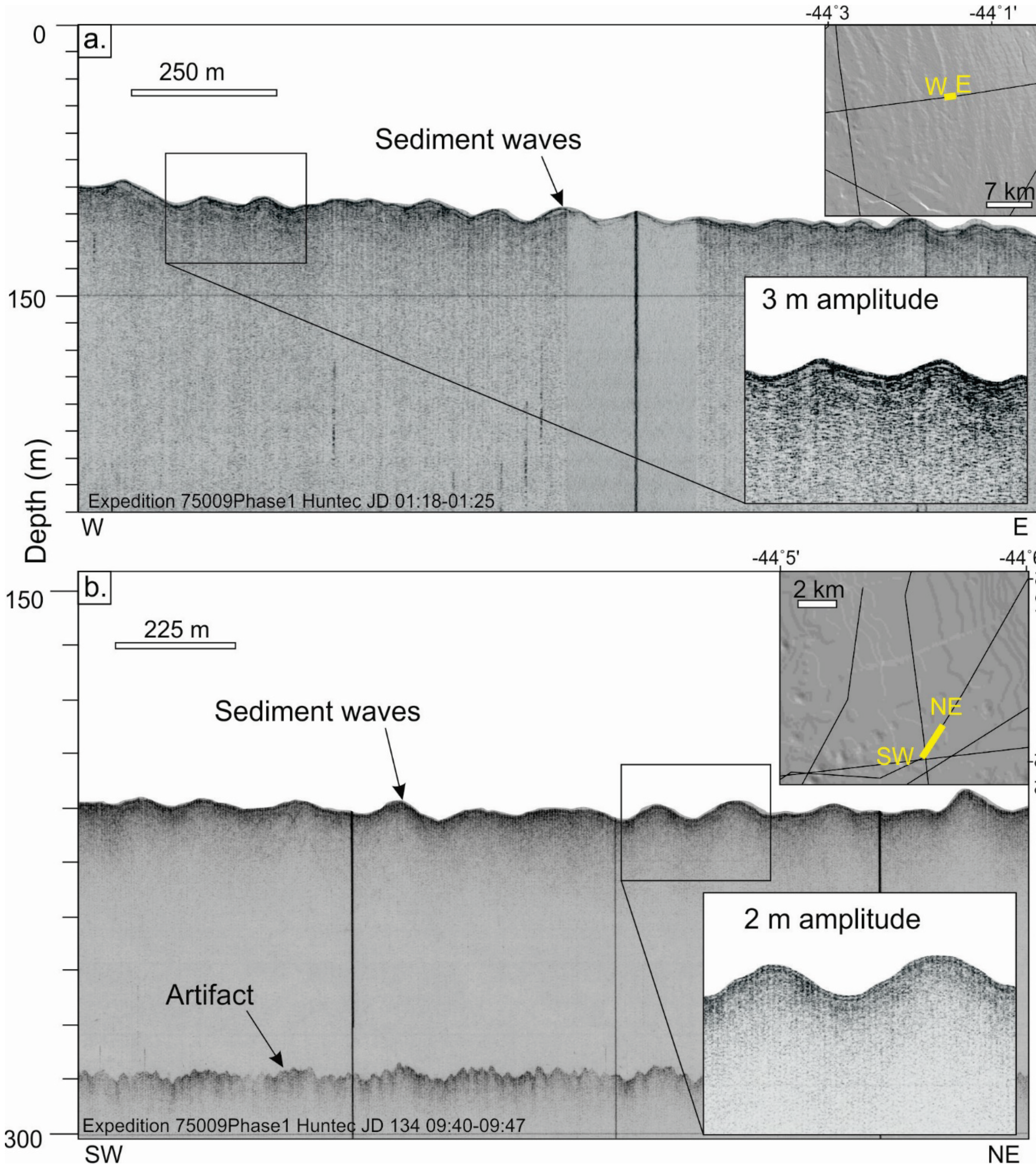

Figure 11 *a) Sediment waves along the northeastern flank of Flemish Cap and their location within the sand ridges in Olex bathymetric data. b) Sediment waves on southeastern Flemish Cap in Huntec data and their location shown in the Olex bathymetric data. Olex shaded-relief inset map shows location of seismic profiles (oceanDTM, n.d.).*

The grain size of surface samples collected on Flemish Cap ranges from gravel to clay with an average grain size of 20% gravel, 57% sand and 23% mud (17% silt and 6% clay) (Figure 4; appendix A). While the samples are all relatively coarse grained, and mud makes up a minority of most samples on top of Flemish Cap, no pattern emerges as to where more gravel or sand dominate samples occur. Patterns could be difficult to resolve with the sparsity of the samples (Figure 4). The limit of this sand and gravel unit is denoted by a stippled unit over the entire cap, as its distinction from the underlying till and bedrock units is not resolved by the acoustic data.

The origin of the patchy sand and gravel cover distributed across Flemish Cap is likely a combination of sediment carried by currents and IRD (Mao et al., 2014). The sand waves were likely sculpted beneath currents flowing across the seabed on Flemish Cap (Wynn and Stow, 2002). The majority of the lithologies of the sediments collected from Flemish Cap are different from the local bedrock (Miles 2018), suggesting these sediments were likely supplied through ice-rafting and likely with a minor contribution coming from the sandstone bedrock (Pe-Piper et al., 2018). It was likely transported by ice-rafting over the past 130,000 years from northern sources and eroded from till or exposed bedrock. The LC supplies icebergs that move south which would deposit IRD across the cap. These icebergs have likely been crossing Flemish Cap since the end of the LGM and imprinting the seabed as iceberg pits and scours. The modern seabed is likely composed of a mix of relict and modern souring from the LGM to present (Shaw 2006). The fine-grained facies contribution has been interpreted as Holocene Hemipelagic sediments and mid-Wisconsin glacial sediments (Miles, 2018).

SURFICIAL FEATURES

Five classes of seafloor features have been superimposed over the broad low relief morphology of the top of Flemish Cap (Figure 2).These include mega scale glacial lineations, eroded bedrock lineations, a glacial moraine, erosional ramp and iceberg scours (Figure 12).

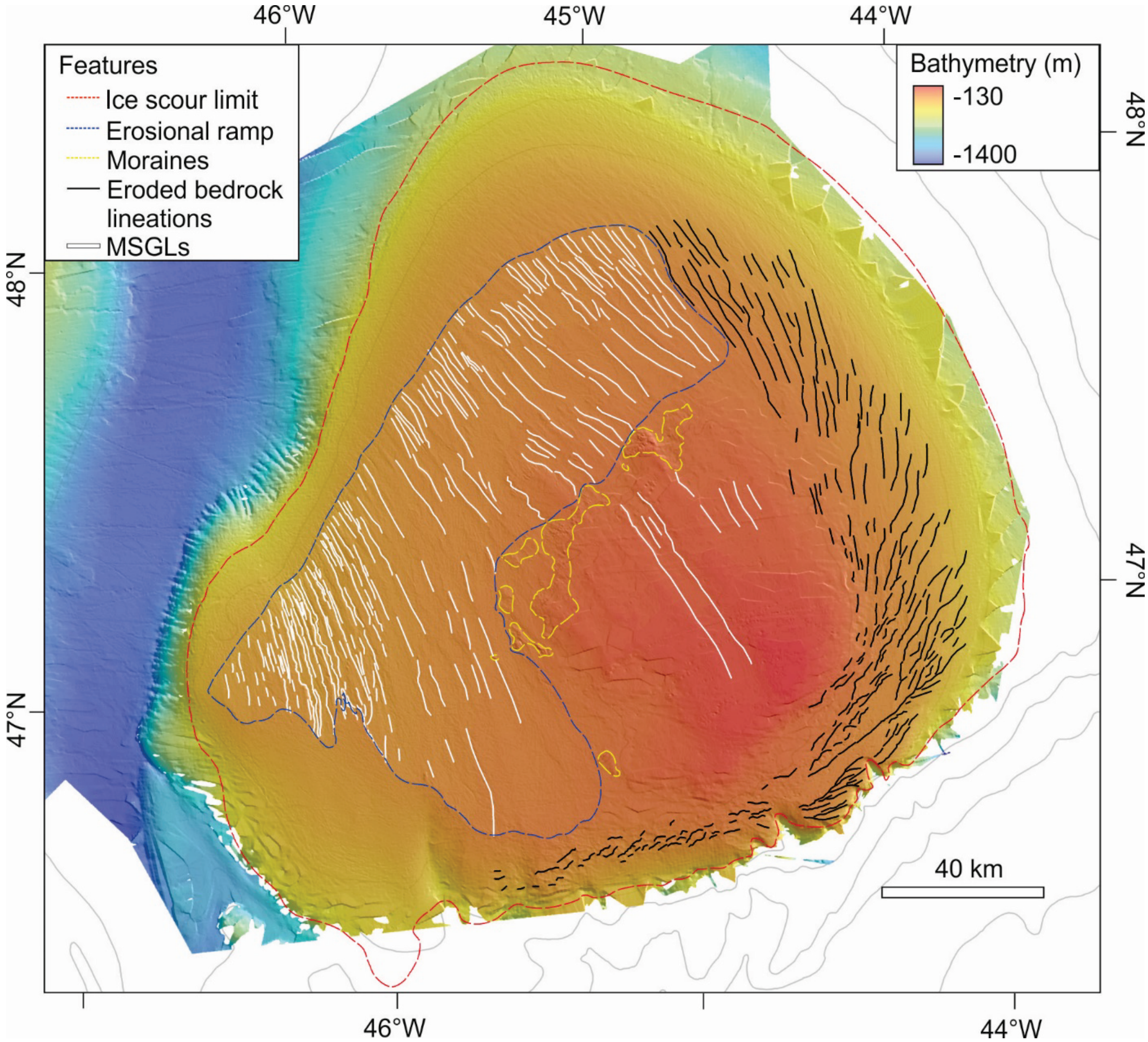

Figure 12 *Surficial features map of Flemish Cap showing: lower ice-scour limit (within dashed red line), erosional ramp (within blue line), MSGLs (white lines), eroded bedrock lineations (black lines) and glacial moraines (within yellow lines). The white lines define the sides of the MSGLs. Shaded relief and colourized Olex bathymetric data underlie the map* (oceanDTM, n.d.).

MSGLs and Erosional Ramp

Large linear and curvilinear surficial features identified on Olex bathymetric data are interpreted as Mega Scale Glacial Lineations (MSGLs) (Figure 12; Figure 13). These MSGLs are best observed in the western and northern areas of Flemish Cap in Olex data, and are illustrated in Figure 14.

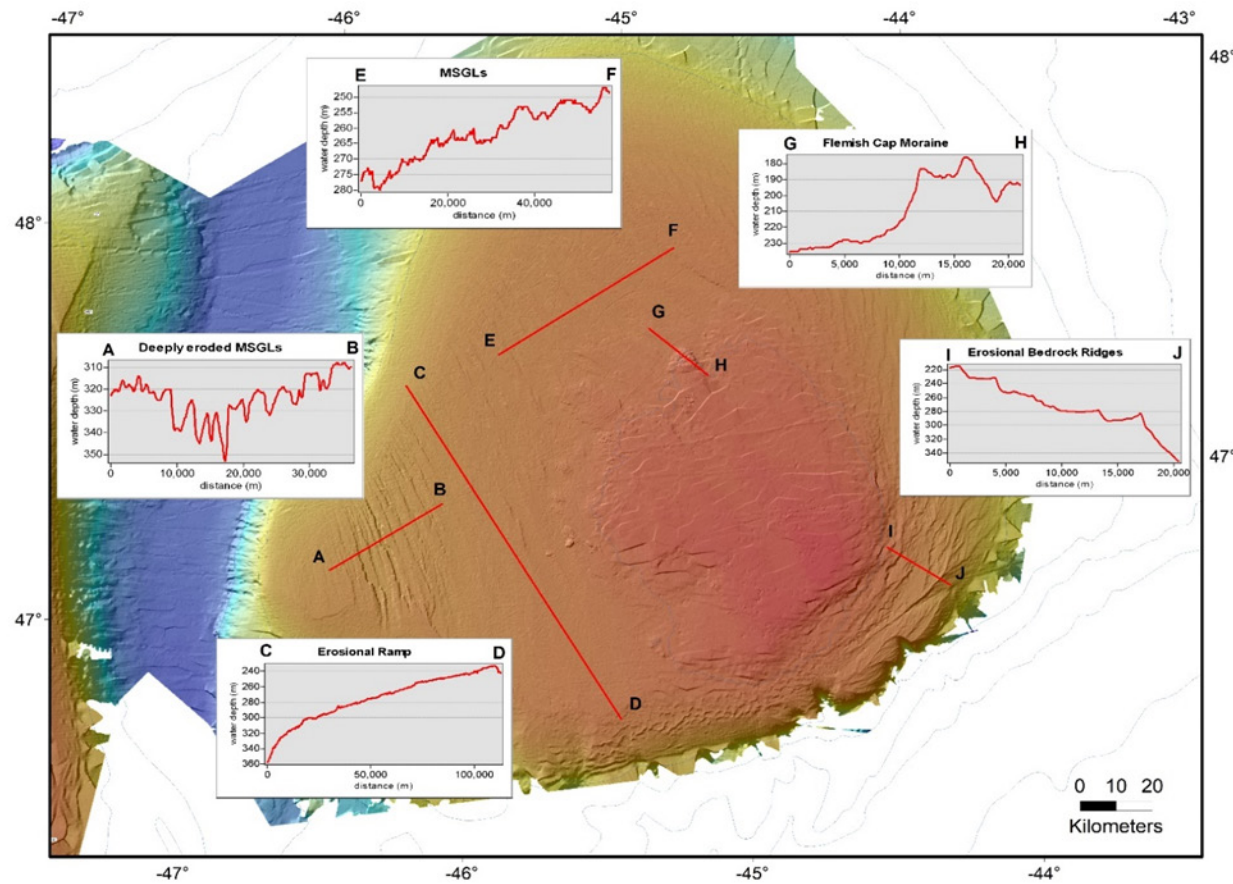

Figure 13 *MSGLs in western Flemish Cap can be up to 28 m deep, profile A-B, while in the north they are shallower (10 m) but wider at up to 8 km, profile E-F. Bathymetric profile, C-D shows a flat erosional ramp formed by erosive glacial ice. A glacial moraine has been identified and shows in profile G-H that it can be up to 40 m high, 5 km across and about 50 km long. Branching and asymmetric pin-wheel-like eroded bedrock lineations are found in the eastern and southern areas of Flemish Cap, profile, I-J. Shaded relief and colourized Olex bathymetric data underlie the profiles* (oceanDTM, n.d.).

MSGLs in the west can be over 54 km long, 3.5 km wide and over 28 m deep (Figure 13, profile A-B). These MSGLs commonly have ragged edges and shallow from north to south starting around 380 m and ending in 300 m water depth. MSGLs in north central Flemish Cap, can be up to 57 km long, 7-8 km wide and 10 m deep. They start in about 305 m water depth and shallow to the south at 212 m. These very large scours cut into soft K-C bedrock or till.

The erosional ramp begins in the north at about 305 m water depth and shallows to the south at 212 m and in the west from 380 m to 300 m water depth. The erosional ramp is approximately 80 km across from north to south and approximately 160 km across from east to west with a area of over 9300 km^2.

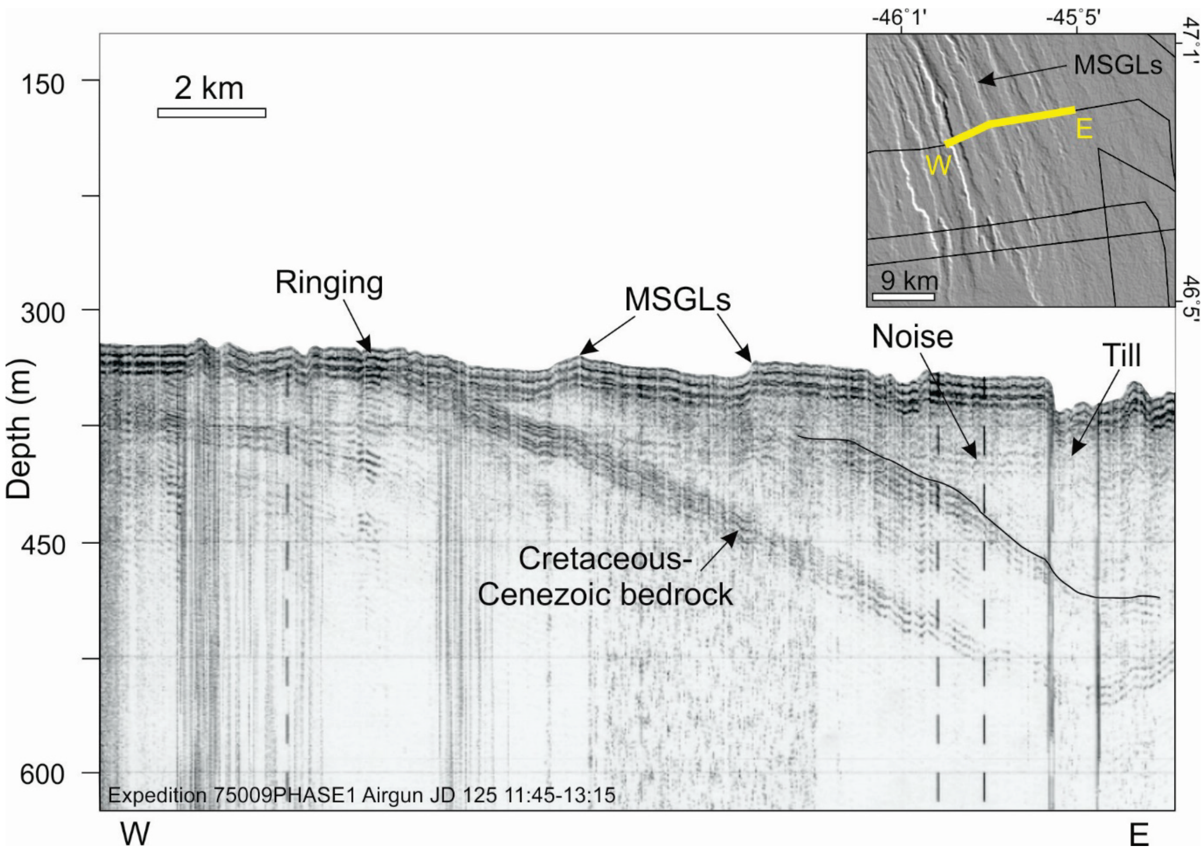

Figure 14 *MSGLs shown as lows in airgun data, with width identified between arrows, on the southwestern surface of Flemish cap cut into K-C bedrock. Olex shaded-relief inset map shows location of seismic profiles (oceanDTM, n.d.).*

The MSGLs were created as glacial ice moved from north to south across Flemish Cap raking and gouging the seafloor, likely driven by ocean currents (Figure 15). The erosional ramp developed as the glacial ice moved from north to south across Flemish Cap, eroding the bedrock and till, while at the same time cutting MSGLs deeper into the seafloor, (Figure 12; Figure 13). Figure 15 illustrates the possible ice flow directions on Flemish Cap, with ice flowing more around the erosionally resistant Neoproterozoic bedrock in the shallower areas of Flemish Cap.

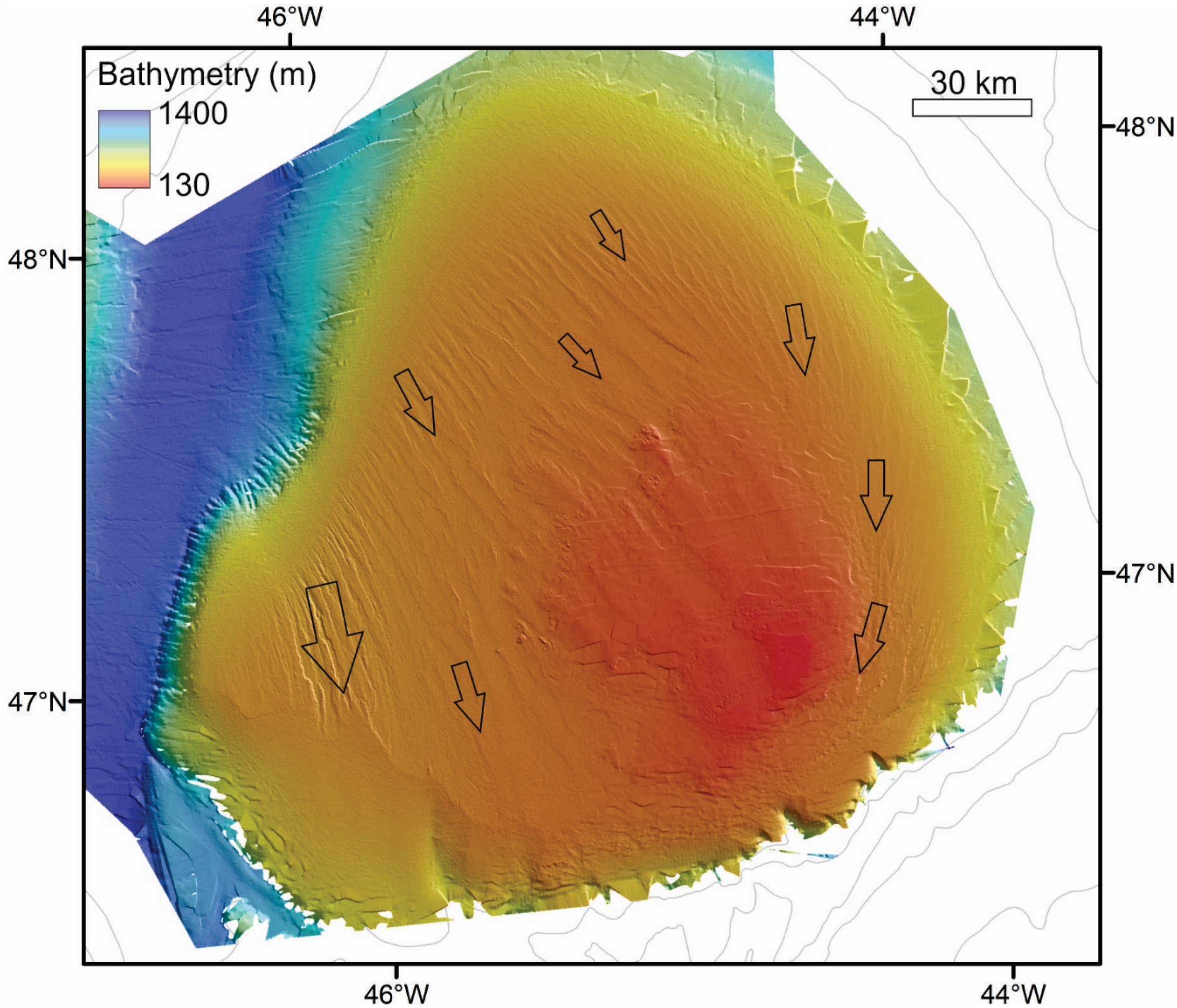

Figure 15 *Possible ice-flow direction by glacial ice-cap that was present on Flemish Cap possibly during the penultimate glaciation. Shaded relief and Olex bathymetric data is shown below (oceanDTM, n.d.).*

Eroded Bedrock Lineations

Branching and asymmetric curvilinear eroded bedrock features are found in the eastern and southern areas of Flemish Cap (Figure 12; Figure 13; Figure 16). Based on their morphology these are interpreted to represent eroded bedrock lineations or ridges. These sometimes sinuous and irregular features shallow northeast to southwest, are up to 40 km long, 13 m high and are found between 230-330 m water depths.

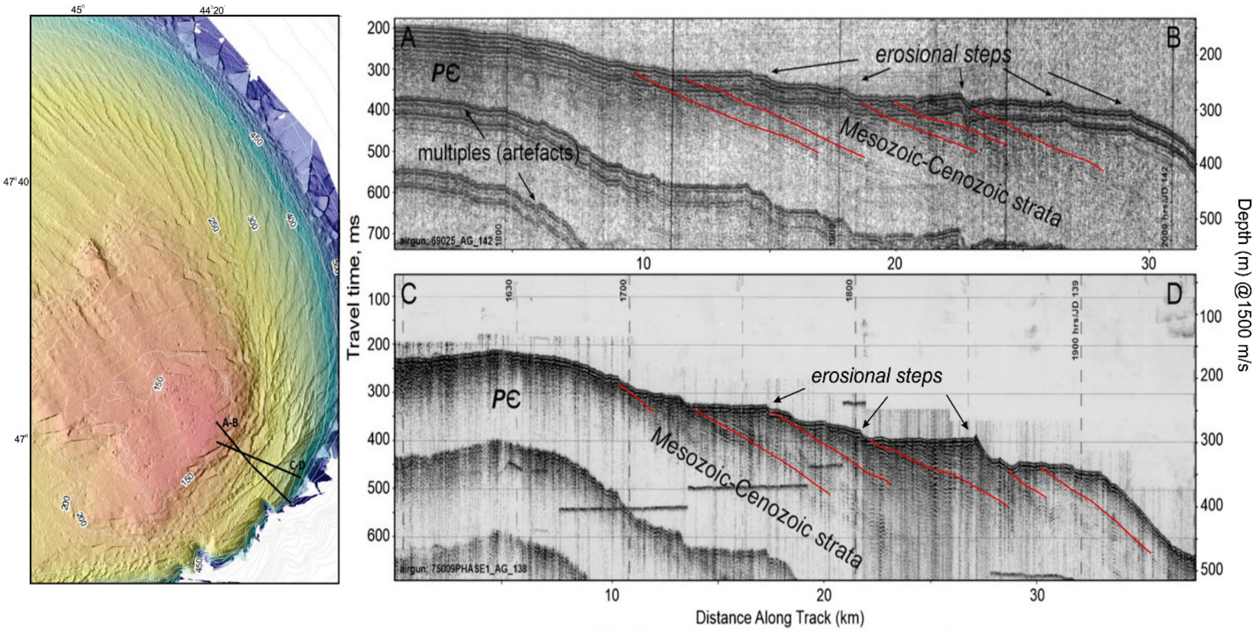

Figure 16: *Branching and asymmetric curvilinear eroded bedrock lineations cut into K-C bedrock in the southern and eastern region of Flemish Cap. These lineations show a partial pin-wheel-like pattern on the Olex shaded-relief map on left. These lineations developed when glacial ice differentially eroded up-dipping beds (red lines) creating steps and ridges in the bedrock, as shown on airgun profiles at right, with locations shown (black lines) on Olex map at left.*

These eroded bedrock lineations developed when glacial ice differentially eroded up-slope dipping K-C beds that onlap the Neoproterozoic core of Flemish Cap, creating a partial pin-wheel appearance that wraps around the eastern side of the cap (Figure 12; Figure 16). They have a step-like appearance in profile because of the up-slope dipping bedrock strata, (Figure 13; Figure 16). There are significant erosional features in the K-C bedrock. It is impossible to tell how much erosion might have occurred, however the presence of deep MSGLs and eroded glacial lineations are indication of a great deal of erosion. These glacial features are consistent with the hypothesis that there was an ice cap on Flemish Cap. These features appear mostly on the K-C beds, while the more resistant Neoproterozoic bedrock core appears to have only a few MSGLs.

Moraine?

Rough, mounded sediment deposited at the terminus of the MSGLs, on northern Flemish Cap, forms a possible moraine (Figure 12; Figure 13; Figure 17). The moraine trends north-east south-west and is oriented perpendicular to the ice flow direction. This moraine is as much as 40 m high (see profile G-H in Figure 13), 7.5 km across and about 50 km long. The moraine likely developed during the penultimate glaciation when glacial ice moved from north to south across Flemish Cap depositing sediment originating mostly from the erosion of the MSGLs and cutting of the erosional ramp (Figure 15; Figure 17). This moraine may be mostly bedrock controlled and may consist of rough bedrock debris likely of more resistant Neoproterozoic rock.

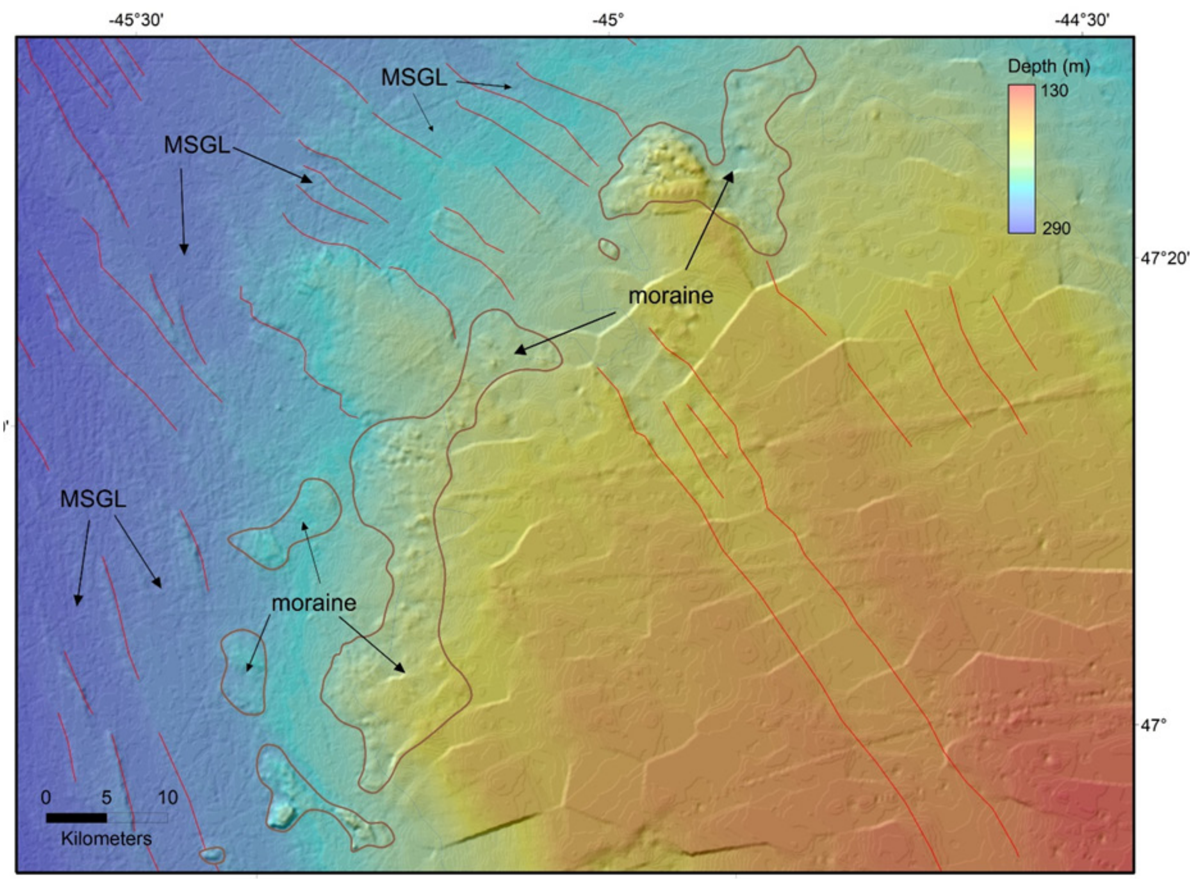

Figure 17 *Detailed view of a possible discontinuous moraine. This moraine developed as the glacial ice deposited eroded sediment at the terminal end of many of the MSGLs. The red lines define the sides (width) of the MSGLs. Shaded relief and Olex bathymetric data is shown below (oceanDTM, n.d.).*

Iceberg scours

Ice-berg scours are observed across Flemish Cap as distinct seafloor sediment plow marks in Huntec seismic reflection profiles (Figure 3), 3.5 kHz sub-bottom profiles (Figure 18) and in Olex data (Figure 19). They occur in the till and gravel cover, above water depths of 650 m (Figure 12; Figure 18) and appear as discrete depressions in the seafloor in seismic profiles (Figure 18). Recent scours are generally 20–30 m wide and less than a meter deep and up to 15 km long (Parrott et al., 1990), but relict Pleistocene scours extend to water depths of 600 m, are 2–3 m deep and may be more than 50 m wide (Piper and Pereira, 1992). They do not have substantial sediment cover in profile data (Figure 18).

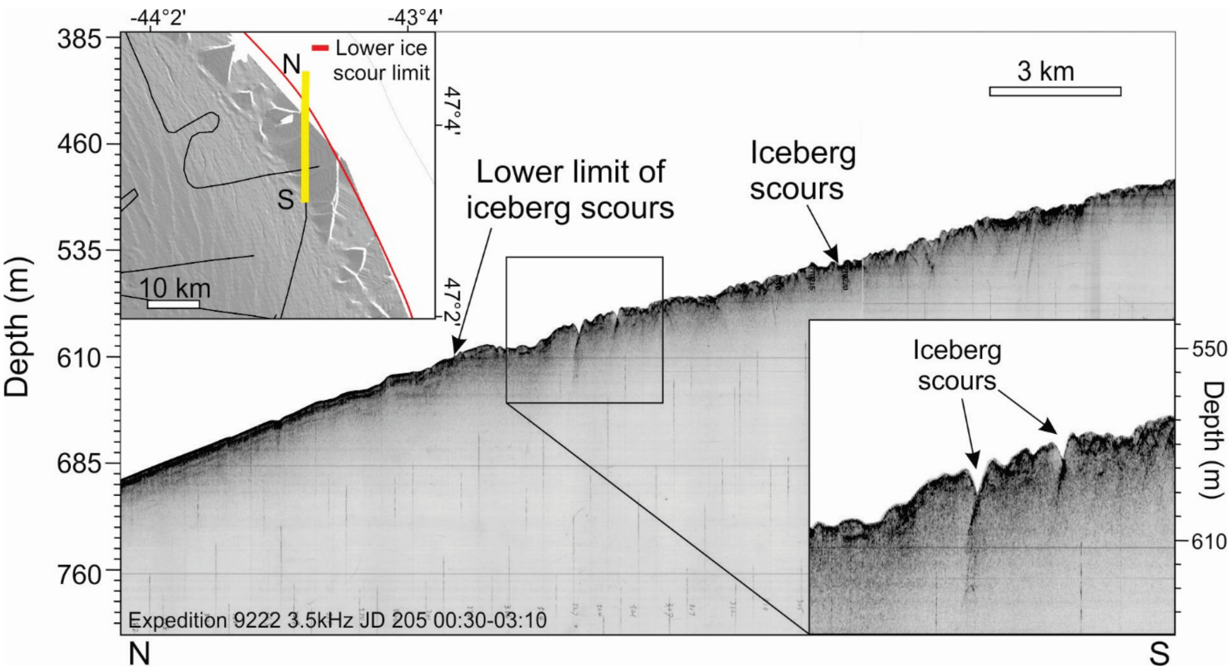

Figure 18 *Iceberg scours and iceberg turbated seabed in 3.5 kHz sub-bottom profiler data showing their lower limit and depth of scouring. Shaded relief of Olex bathymetric data underlies figure location (oceanDTM, n.d.).*

The Olex data show the seabed is densely ice scoured, with scours more than 30 kms long and more than 100 m wide in places, (Figure 19). These ice scours cross-cut the MSGLs suggesting they are younger and may be from the penultimate glaciation or younger.

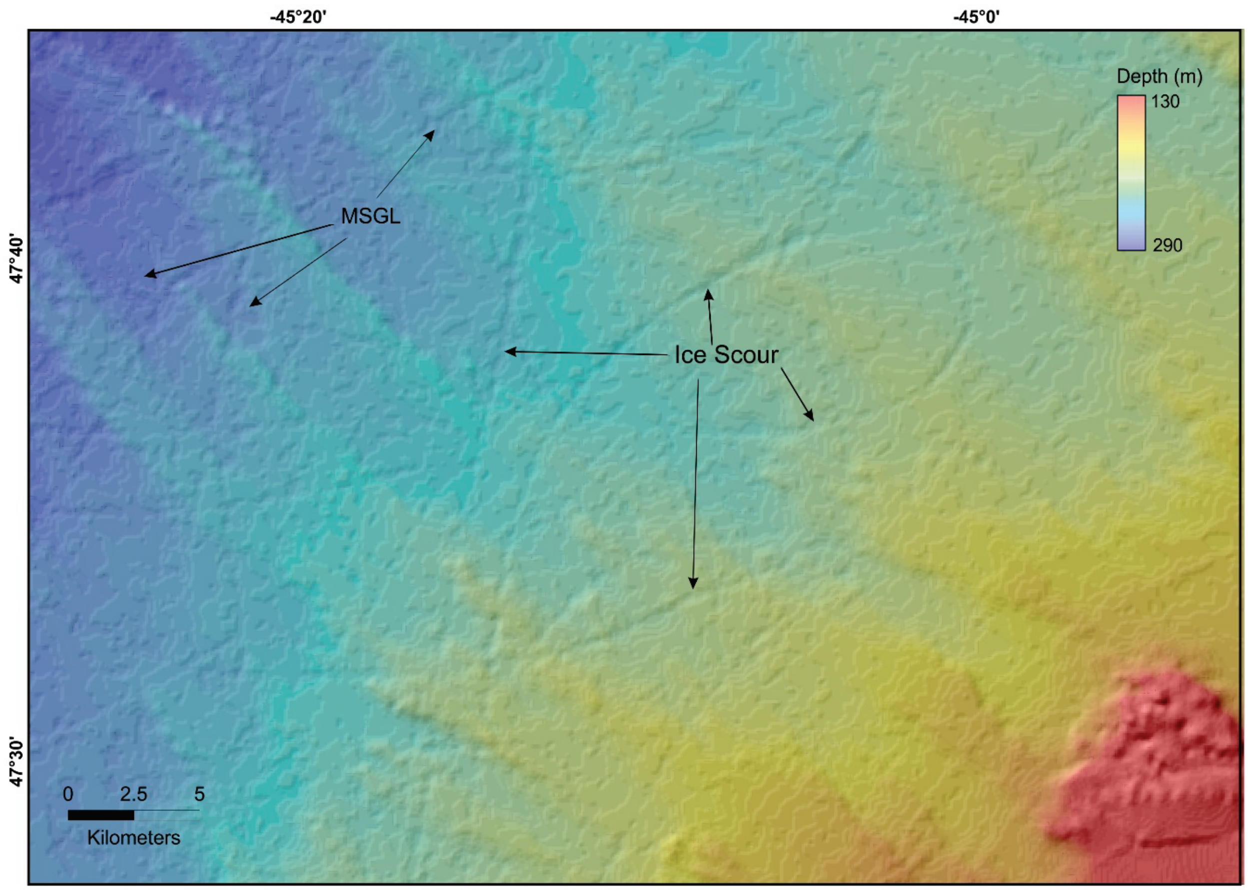

Figure 19 *The Olex data shows the seabed (north side of moraine) is densely ice scoured. These ice scours cross-cut the MSGLs suggesting they are younger and may be from the penultimate glaciation or younger. Shaded relief of Olex bathymetric data underlies figure location (oceanDTM, n.d.).*

Synthesis of surficial features

Based on the observed geological features a sequence of events can be postulated for Flemish Cap. During the penultimate glaciation it is hypothesized that a glacial ice cap formed on Flemish Cap (Stacey, 2011). Morphological evidence including MSGL and other very large erosional features suggest a significant amount of erosion of the softer K-C bedrock unit by glacial action before a till unit was deposited. The till suggests a phase of deposition under glacial ice following the erosion of the K-C bedrock. To produce the observed MSGLs and bedrock lineations, glacial ice could have moved across Flemish Cap (Figure 15) gouging the bedrock and till units. The higher relief and more resistant

Neoproterozoic bedrock likely acted as a partial barrier to ice flow, and so ice likely moved mostly around the more resistant bedrock (Figure 15). This is supported by the formation of a transverse moraine that represents a transition point between a zone of continuous MSGL on the north (upflow) end and a zone that is scarce in erosive features to the south. During the LGM Flemish Cap was likely not glaciated and some of Flemish Cap would have been close to sea-level and reworked by high-wave energy (Shaw, 2006). Since the LGM, ice rafted debris have been delivered to Flemish Cap, while icebergs scoured the seabed and bottom currents winnowed and redistributed the seafloor sediment and likely forming sand waves during this time.

LIMITATIONS

The main constraint in interpolating the surficial geology of Flemish Cap is the limited data coverage. There is a noticeable absence of seismic reflection profiles towards the northern flank of the cap and towards the southwestern flank (Figure 3). There is also a limited amount of high resolution Huntec and 3.5 kHz data coverage (Figure 3). The data quality is also limited, as many of the seismic reflection profiles were collected in the 1960-1970s and are of poorer quality. No new seismic data has been collected in the area since 2001, although the Olex bathymetry has provided the most recent data to improve the surficial geology mapping. It is also important to note that the sediment cover is based on sparse grain size data from grab samples and is generalized over a large area. No cores have penetrated the till unit which would be required to ground truth the interpretation.

CONCLUSIONS

This report outlines the surficial geology of Flemish Cap based on the latest data available in the region. Three main surficial geology units can be denoted on the top of Flemish Cap including bedrock, till and sand and gravel cover. The bedrock includes Neoproterozoic granodiorite and granite overlain by K-C sedimentary rocks, which are subsequently overlain by till. Below 500-600 m water depth, sediment drift deposits occur. On top of the majority of Flemish Cap is patchy sand and gravel cover, which are likely sourced by icebergs depositing IRD across the cap. Iceberg scours are observed across Flemish Cap above water depths of 650 m.

MSGLs and eroded bedrock lineations wrap around Flemish Cap. MSGLs developed as glacial ice moved across Flemish Cap from north to south (Figure 15; Figure 17) while also cutting an erosional ramp in the soft bedrock and glacial deposits (Figure 16). A possible moraine developed as the glacial ice pushed the eroded sediment and deposited it at the terminal end of the MSGLs. The glacially eroded bedrock lineations underwent differential erosion of less resistant up-slope dipping K-C beds that wrap around the eastern and southern Flemish Cap. Further erosion of these features may also have occurred from bottom currents.

The presence of till, deep MSGLs and truncated beds, all indicative of glacial erosion, provide further evidence for an ice cap on Flemish Cap during MIS 6. Data is limited on Flemish Cap, as seismic data is sparse and concentrated over the center of the cap and sediment samples do not penetrate the till unit. The bathymetric coverage of the area has been greatly improved by the Olex bathymetry and this has provided new insights into the distribution and morphology of sediments deposited on Flemish Cap.

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APPENDIX A

Table 1: Grain size for surficial sediment samples collected from Flemish Cap.

Expedition	Station #	Sample Type	Latitude	Longitude	Water Depth (m)	Sample interval (cm)	% Gravel	% Sand	% Silt	% Clay
2008NEREIDA	114	Box core	48.0	-45.7	468	0-5	43	49	6	2
2008NEREIDA	118	Box core	48.1	-45.2	370	0-5	71	24	3	1
2008NEREIDA	119	Box core	48.2	-45.0	450	0-5	10	68	17	5
2008NEREIDA	120	Box core	48.2	-44.9	503	0-5	10	62	21	7
2008NEREIDA	123	Box core	48.3	-44.7	605	0-5	33	34	25	8
2008NEREIDA	150	Box core	47.9	-44.3	476	0-5	9	60	23	8
2008NEREIDA	157	Box core	47.5	-44.0	475	0-5	2	48	40	9
2008NEREIDA	162	Box core	47.5	-44.6	224	0-5	7	83	7	3
2008NEREIDA	165	Box core	47.5	-44.9	218	0-5	10	75	11	4
2008NEREIDA	168	Box core	47.8	-44.9	248	0-5	11	82	5	1
2008NEREIDA	171	Box core	47.7	-45.9	431	0-5	52	42	4	1
2008NEREIDA	173	Box core	47.7	-45.7	302	0-5	10	75	11	4
2008NEREIDA	174	Box core	48.0	-45.5	354	0-5	19	74	5	2
2008NEREIDA	176	Box core	47.9	-45.3	283	0-5	4	84	9	3
2008NEREIDA	179	Box core	47.7	-45.3	264	0-5	28	64	6	2
2008NEREIDA	186	Box core	47.2	-45.0	166	0-5	5	90	4	1
2008NEREIDA	189	Box core	47.2	-44.6	168	0-5	18	78	3	1
2008NEREIDA	191	Box core	47.5	-44.3	290	0-5	1	79	15	5
2008NEREIDA	193	Box core	47.4	-44.0	429	0-5	70	23	4	2
2008NEREIDA	194	Box core	47.3	-44.0	382	0-5	37	57	4	1
2008NEREIDA	195	Box core	47.2	-44.2	290	0-5	12	77	8	3
2008NEREIDA	196	Box core	47.1	-44.0	394	0-5	19	68	10	3
2008NEREIDA	204	Box core	46.9	-43.9	462	0-5	4	84	9	4

Expedition	Station #	Sample Type	Latitude	Longitude	Water Depth (m)	Sample interval (cm)	% Gravel	% Sand	% Silt	% Clay
2008NEREIDA	208	Box core	46.9	-43.9	605	0-5	19	67	11	4
2008NEREIDA	216	Box core	47.0	-44.8	152	0-5	38	57	4	1
2008NEREIDA	217	Box core	47.0	-45.0	149	0-5	32	66	1	0
2008NEREIDA	227	Box core	46.5	-45.9	389	0-5	69	29	1	1
2008NEREIDA	228	Box core	46.5	-46.1	420	0-5	42	48	7	3
2008NEREIDA	229	Box core	46.5	-46.3	456	0-5	0	88	9	3
2008NEREIDA	240	Box core	46.7	-46.4	425	0-5	52	43	4	1
2008NEREIDA	243	Box core	47.0	-46.4	335	0-5	7	77	13	4
2008NEREIDA	245	Box core	47.1	-46.5	387	0-5	49	47	3	1
2008NEREIDA	250	Box core	47.5	-45.5	272	0-5	3	73	18	6
75009PHASE1	9893	Vibrocore	46.8	-45.6	252	4-7	1	98	1	0
75009PHASE1	9895	Grab	47.5	-45.7	290	0	0	68	25	8
77011	2118	Grab	47.4	-44.9	182.8	0	71	6	17	6
Long Harbour	9644	Grab	47.1	-43.9	0	0	0	1	50	48
Long Harbour	9645	Grab	47.1	-43.8	0	0	0	18	66	16
Long Harbour	9646	Grab	47.1	-43.9	0	0	0	73	20	8
Long Harbour	9647	Grab	47.1	-43.9	0	0	0	6	70	24
Long Harbour	9648	Grab	47.1	-43.9	0	0	0	31	53	16
Long Harbour	9649	Grab	47.1	-43.9	0	0	0	28	59	14
Long Harbour	9650	Grab	47.1	-43.8	0	0	0	22	60	18
Long Harbour	9651	Grab	47.1	-43.8	0	0	21	74	4	1
Long Harbour	9652	Grab	47.1	-43.8	0	0	0	93	5	2
Long Harbour	9653	Grab	47.1	-43.8	0	0	34	16	39	11
Long Harbour	9654	Grab	47.1	-43.8	0	0	26	70	3	1
2009061	223	Box Core	46.5	-46.0	730	0	0	79	12	9
						Averages	20	57	17	6